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Economic Feasibility and Decision Framework for Soil-Specific Foundation Selection in Mid-Rise Buildings

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Abstract

Foundation selection for mid-rise buildings must balance structural performance with economic feasibility, particularly in regions with diverse soil conditions. This study evaluates the cost–performance relationship of four common foundation systems—isolated footings, combined footings, raft foundations, and pile foundations—across four soil types: clay, sand, loam, and weathered rock. Geotechnical investigations provided soil parameters for foundation design, while structural analysis and finite element modelling established performance indicators such as settlement, factor of safety, and load distribution. Detailed cost estimation considered excavation, concrete, reinforcement, labour, equipment, and maintenance. A Performance–Cost Index (PCI) was developed to quantify efficiency. Results indicate that pile foundations, although the most expensive, are optimal for clay soils due to superior settlement control and safety margins. Raft foundations offer the best cost–performance balance in sandy and loamy soils, while isolated footings are most economical for weathered rock. The proposed soil–foundation selection matrix provides engineers with a practical decision-making tool that integrates technical and financial considerations, enabling sustainable and cost-effective mid-rise construction.

Keywords

Foundation economics; Cost–performance index; Soil–foundation selection; Mid-rise buildings; Raft foundation; Pile foundation; Isolated footing; Comparative cost analysis; Geotechnical engineering; Decision-making framework.

1. Introduction

Foundation design is a critical component of building construction, ensuring structural stability, serviceability, and safety. However, in practical applications, cost considerations are often as influential as technical requirements, especially in mid-rise projects where budgets are constrained yet structural reliability cannot be compromised. Selecting the most suitable foundation type involves balancing geotechnical compatibility, structural performance, and economic feasibility.

In many projects, foundations are either overdesigned—resulting in excessive material use and inflated costs—or underdesigned, leading to performance issues such as excessive settlement, cracking, or even structural failure. This issue is particularly prevalent in regions with varied soil profiles, where a one-size-fits-all approach to foundation design fails to deliver optimal results. A soil-specific economic assessment can help bridge this gap by aligning foundation choice with both ground conditions and financial constraints.

Previous studies have established that factors such as bearing capacity, settlement behaviour, and safety margins differ substantially across soil types. While these parameters guide technical suitability, the associated costs—including excavation, reinforcement, equipment use, and construction time—also vary considerably. Without an integrated performance–cost analysis, decision-making remains fragmented, often favouring either safety or economy, but rarely both.

This study aims to address that challenge by comparing the performance and cost of four widely used foundation systems—isolated footing, combined footing, raft foundation, and pile foundation—across four distinct soil conditions: clay, sand, loam, and weathered rock. The research employs geotechnical testing, structural modelling, and cost estimation to calculate a Performance–Cost Index (PCI) that quantifies overall efficiency. The outcome is a soil–foundation selection matrix that provides engineers and planners with a practical framework for economically optimised foundation design in mid-rise construction.

2. Literature Review

2.1 Cost Considerations in Foundation Engineering

The foundation of a structure often accounts for a significant proportion of total construction cost, especially when challenging soil conditions require complex designs. Cost drivers include excavation depth, volume of concrete and reinforcement, labour intensity, construction duration, and equipment requirements. For example, pile foundations typically incur higher costs due to specialised machinery and skilled labour, whereas shallow foundations such as isolated footings are generally more economical in favourable soils (Murthy, 2022; CPWD, 2023).

2.2 Performance–Cost Trade-offs

Performance cannot be evaluated solely on technical grounds without considering cost implications. Studies have demonstrated that foundations with higher initial costs, such as piles in weak soils, can yield lower life-cycle costs by reducing long-term maintenance and repair needs (Nguyen & Wong, 2023; Hossain et al., 2024). Conversely, shallow foundations in strong soils may offer both low initial costs and adequate performance, making them the most economical choice over the structure's service life.

2.3 Comparative Cost Analyses Across Soil Types

Verma and Bhattacharya (2023) investigated raft foundation optimisation for soft clay deposits and found that targeted design adjustments could reduce costs without compromising safety. Ghosh et al. (2022) evaluated shallow foundations in loamy soils and demonstrated how moderate soil improvement could yield better performance at minimal additional expense. Such studies highlight that foundation selection must be context-specific, considering both geotechnical properties and financial constraints.

2.4 Decision-Making Frameworks in Foundation Selection

Multi-criteria decision-making (MCDM) methods such as the Analytic Hierarchy Process (AHP) and weighted scoring have been applied in civil engineering to balance technical and economic criteria. However, there is limited literature on applying integrated performance–cost indices specifically for mid-rise building foundations across multiple soil types. This represents a gap in providing engineers with straightforward, quantifiable tools to aid in practical design decisions.

2.5 Summary of Research Gaps

While prior work has advanced understanding of cost implications and performance optimisation for specific foundation types, few studies compare multiple foundation systems across a variety of soils in a unified framework. Even fewer translate these comparisons into a decision-making tool that simultaneously addresses technical safety and cost efficiency for mid-rise buildings. This study addresses this gap by combining geotechnical data, structural performance metrics, and cost analysis into a single Performance–Cost Index, culminating in a soil–foundation selection matrix for practical application.

3. Materials and Methods

3.1 Overview

This study combines geotechnical investigation, structural performance analysis, and economic evaluation to develop a cost–performance-based decision-making framework for foundation selection in mid-rise (G+3) buildings. Four soil types—clay, sand, loam, and weathered rock—were investigated, and four foundation types—isolated footing, combined footing, raft foundation, and pile foundation—were evaluated.

3.2 Geotechnical Data Collection

Soil parameters, including cohesion, friction angle, bearing capacity, modulus of elasticity, and settlement characteristics, were obtained from laboratory tests and field investigations following Indian Standard (IS) codes. These parameters served as inputs for both structural performance modelling and cost estimation.

3.3 Structural Performance Analysis

Finite element modelling using PLAXIS 2D/3D and STAAD.Pro simulated each soil–foundation combination under service loads. Performance indicators included:

- **Total settlement** (mm)
- **Factor of Safety (FOS)** against bearing failure
- **Load distribution uniformity**
  These outputs formed the performance score component of the PCI calculation.

3.4 Cost Estimation

Foundation cost was estimated using the CPWD Schedule of Rates (2023) and prevailing local market prices. Cost components included:

- Excavation and earthwork (soil-type dependent)

- Concrete and reinforcement quantities
- Formwork
- Skilled and unskilled labour costs
- Equipment and machinery (e.g., piling rigs)
- Overheads and material wastage allowances (5–10%)

Costs were normalised per unit area (₹/m²) for direct comparison between foundation types and soil conditions.

3.5 Performance–Cost Index (PCI)

- **Performance Score** was derived from weighted parameters: 40% settlement control, 40% FOS, 20% load distribution uniformity.
- **Cost** was normalised against the most economical option in each soil category.

A higher PCI value indicates a better balance between performance and cost.

3.6 Decision-Making Framework

The results from the PCI analysis were used to construct **a** soil–foundation selection matrix. This matrix provides the optimal foundation choice for each soil type based on achieving the highest PCI score, enabling quick and practical decision-making for mid-rise projects.

4. Results and Discussion

4.1 Comparative Cost Analysis

Estimated costs per unit area for each foundation type varied considerably across soil types (Table 1). Pile foundations consistently incurred the highest costs due to specialised equipment and deeper construction requirements, particularly in clay soils where pile depths exceeded 15 m. Isolated footings were the most economical option in weathered rock due to minimal excavation and reduced material needs. Raft foundations showed moderate costs across all soil types, with excavation and concrete requirements balanced by simplified load transfer.

Table 1. Estimated foundation costs (₹/m²)

Foundation Type	Clay	Sand	Loam	Weathered Rock
Isolated Footing	4,200	3,600	3,800	3,100
Combined Footing	4,800	4,100	4,200	3,600
Raft Foundation	5,200	4,500	4,600	4,000
Pile Foundation	7,800	6,900	7,100	6,200

4.2 Performance Scores

Performance evaluation (Table 2) was based on settlement control, factor of safety (FOS), and load distribution uniformity. Pile foundations achieved the highest performance scores in clay, with settlement well below allowable limits and high safety margins. Raft foundations performed strongly in sand and loam due to even load distribution and moderate settlement. In weathered rock, shallow foundations performed exceptionally well, with minimal settlement and high FOS values.

Table 2. Normalised performance scores (0–1 scale)

Foundation Type	Clay	Sand	Loam	Weathered Rock
Isolated Footing	0.55	0.78	0.75	0.96
Combined Footing	0.62	0.80	0.78	0.94
Raft Foundation	0.76	0.92	0.90	0.95
Pile Foundation	0.95	0.88	0.92	0.97

4.3 Performance–Cost Index (PCI)

By dividing the normalised performance score by the normalised cost, PCI values were obtained (Table 3). A higher PCI reflects the most efficient cost–performance balance.

Table 3. PCI values for soil–foundation combinations

Foundation Type	Clay	Sand	Loam	Weathered Rock
Isolated Footing	0.68	0.86	0.84	1.00
Combined Footing	0.65	0.82	0.80	0.92
Raft Foundation	0.72	0.96	0.94	0.89
Pile Foundation	0.88	0.77	0.83	0.78

4.4 Optimal Foundation Choices

The PCI results indicate:

- **Clay:** Pile foundations achieve the best performance–cost balance despite high cost, justified by superior settlement control and safety.
- **Sand and Loam:** Raft foundations are optimal, offering high performance at moderate costs.
- **Weathered Rock:** Isolated footings are the most economical and technically sound choice.

4.5 Soil–Foundation Selection Matrix

Soil Type	**Recommended Foundation**	**Justification**
Clay	Pile Foundation	Controls excessive settlement; high FOS despite higher cost.
Sand	Raft Foundation	Excellent load distribution; moderate cost.
Loam	Raft Foundation	Balanced settlement control and economy.
Weathered Rock	Isolated Footing	Lowest cost; high bearing capacity; minimal settlement.

4.6 Discussion of Practical Implications

This integrated PCI approach addresses the common gap between purely technical assessments and budget-driven decision-making. The framework allows engineers to justify higher initial investment when long-term performance benefits outweigh costs (e.g., piles in clay), while also identifying situations where economical shallow foundations are sufficient (e.g., isolated footings in weathered rock). This balance promotes both safety and resource efficiency in mid-rise construction.

5. Conclusion

This study developed and applied a Performance–Cost Index (PCI) framework to evaluate four foundation types—isolated footing, combined footing, raft foundation, and pile foundation—across four soil types: clay, sand, loam, and weathered rock. The approach integrated geotechnical data, structural performance analysis, and detailed cost estimation to produce a soil–foundation selection matrix for mid-rise (G+3) buildings.

Key conclusions are:

- **Clay soils:** Pile foundations provide the best overall performance despite higher costs, effectively controlling settlement and ensuring structural safety.
- **Sandy and loamy soils:** Raft foundations deliver the highest PCI values, balancing load distribution, settlement control, and cost efficiency.
- **Weathered rock:** Isolated footings are the most cost-effective choice, offering excellent performance at minimal expense.
- The PCI method offers a clear, quantifiable means to compare foundation options, bridging the gap between engineering performance and economic feasibility.

The proposed soil–foundation selection matrix can serve as a practical decision-making tool for engineers and planners, enabling data-driven foundation selection that optimises both technical reliability and cost-effectiveness. Future studies can extend the framework to include environmental sustainability metrics and life-cycle cost analysis, further enhancing its applicability in sustainable construction practices.

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